Radiation Protection Dosimetry (2004) Vol. 112, No. 3, pp. 405–418
Advance Access publication 19 October 2004
doi:10.1093/rpd/nch410

INFLUENCE OF RADIONUCLIDES DISTRIBUTED IN THE WHOLE BODY ON THE THYROID DOSE ESTIMATES OBTAINED FROM DIRECT THYROID MEASUREMENTS MADE IN BELARUS AFTER THE CHERNOBYL ACCIDENT

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Received April 15 2004, amended September 7 2004, accepted September 19 2004

Thyroid dose reconstruction is most accurate when using the results of direct thyroid measurements, in which gamma radiation emitted by radionuclides present in the thyroid and in the remainder of the body is recorded by means of a radiation detector positioned against the neck. A large number of such measurements were performed in Belarus in May–June 1986. Owing to the short half-life of ^{131}I and to the intake and accumulation of caesium radioisotopes (mainly ^{134}Cs and ^{137}Cs) in the body, the thyroid doses derived from thyroid measurements made after the beginning of June 1986 have so far been often considered to be unreliable. To evaluate the influence of the caesium radioisotopes to the signal recorded by an instrument performing measurement of ^{131}I activity in the thyroid, a Monte Carlo method was used to calculate the calibration factors of that instrument. These calculations were made for males of six reference ages: newborn, 1, 5, 10 and 15 years old, and adult. The calibration factors were combined with estimated time-dependent intake functions for ^{131}I and caesium radioisotopes. The fractions of the instrument indications that were due to ^{131}I in thyroid were thus estimated as a function of the age of the subject that was measured and of the time elapsed since the accident. Using this information when processing the thyroid measurements made in May 1986 would improve the accuracy of the thyroid dose estimates, and may make it possible to use a larger proportion of the thyroid measurements made in June 1986.

INTRODUCTION

Following the Chernobyl accident on 26 April 1986, an increase in childhood thyroid cancer has been reported for the time period 1990–1992 in Belarus(1–2) and in Ukraine(3), and later on in Russia(4). Investigative studies generally confirm that the increase in the thyroid cancer incident is real(5) and that it likely is related to radiation exposure resulting from the Chernobyl accident(6–8). To carry out detailed studies of the relationship between the thyroid dose and thyroid cancer, it is necessary to provide reliable dosimetric information.

The best available estimates of thyroid dose are based on the results of direct thyroid measurements, in which gamma radiation emitted by radionuclides present in the thyroid and in the remainder of the body is recorded by means of a radiation detector positioned against the neck. Many direct thyroid measurements were made during the first weeks after the accident in Belarus and elsewhere, and have been used for thyroid dose reconstruction(9–11). During the first month after the accident, most of the signal recorded by the detector was due to the ^{131}I activity in the thyroid. However, a fraction of these measurements was conducted in June 1986, more than five weeks after the accident. The direct thyroid measurements made in this time period have often been considered to be unreliable for thyroid dose reconstruction because ^{131}I in the thyroid had decayed substantially whereas the activity of long-lived radiocaesium (^{134}Cs and ^{137}Cs) in the body was increasing. This resulted in a contribution of non-iodine radiation to the response of the dosimetric instrument used in the measurement campaign and, consequently, to an overestimation of the thyroid dose. To evaluate a possibility of using late measurements for the thyroid dose reconstruction, the influence of long-lived radiocaesium present in the whole body on the response of detectors placed against the thyroid has to be assessed.

The present paper deals with a specific instrument, namely SRP-68-01, which was widely used for the direct thyroid measurements in May–June 1986. For this instrument, age-dependent calibration factors for the measurement of ^{131}I in the thyroid and of radiocaesium in the whole body have been obtained by Monte Carlo simulation of radiation transport in

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the human body and in the instrument's detector. Human bodies of different ages have been modelled by means of mathematical phantoms.

Estimation of the fraction of the instrument reading that is due to ^{131}I in thyroid and the fraction that is due to radiocaesium in the whole body has been performed using a radioecological model adapted to local conditions of Belarus. This model has been used to estimate the variation with time of the human intakes of ^{131}I and radiocaesium as a function of age. Metabolic models are then used to estimate the age and time dependence on the contents of ^{131}I in thyroid and radiocaesium in the whole body.

The influence of radiocaesium on the instrument reading depends on how the radiation background was determined and on whether a collimator was used to shield the detector from radiation originating from locations other than the thyroid of the person. As a rule, collimators were not used in Belarus; also, in many instances the radiation background was not measured, or was measured in the room in the absence of the subject[9]. Under those circumstances, the influence of radiocaesium needs to be assessed.

However, when the radiation background was measured by placing the detector near the shoulder or the liver, the influence of radiocaesium on the instrument reading was adequately taken into account, and no correction was needed.

Another aspect of the problem should be mentioned here. In addition to internal contamination, the skin, hair and clothes of the persons measured were often contaminated, leading to an additional contribution to the signal recorded by the detector. The determination of the contribution due to external contamination is a difficult problem that is under consideration. For the purposes of this paper, it is assumed that the external contamination of the persons who were measured was negligible.

METHODS

Raw data of thyroid measurements with the survey-meter SRP-68-01 are primarily instrument indications in units of exposure rate—mR h^{-1}. The instrument indication can be represented as a sum:

$$X_{\text{meas}} = X_{\text{b}} \cdot k_{\text{att}} + \sum_i X_i + X_{\text{other}}, \tag{1}$$

where

X_{b} = background in the place of measurement; this includes all radiation sources other than the person measured;

k_{att} = a factor accounting for the attenuation of the background due to shielding by the body of the person measured;

X_i = reading of the instrument caused by radiation emitted by internally distributed nuclide i;

X_{other} = reading of the instrument caused by external contamination from skin, clothes or hair of the person measured.

In the following consideration, we will neglect the attenuation of the background due to shielding by the human body ($k_{\text{att}} = 1$) and the external contamination of the measured person ($X_{\text{other}} = 0$). This will lead to Equation 1 to be written as

$$X_{\text{meas}} = X_{\text{b}} + \sum_i X_i = X_{\text{b}} + X_{\text{net}}, \tag{2}$$

where X_{net} is the net exposure rate due to internally distributed radionuclides.

The contribution of a specific nuclide j (in the group of nuclides i) to the instrument indication, X_j, can be expressed as:

$$X_j = F_j \cdot X_{\text{net}} = F_j \cdot \sum_i X_i = F_j \cdot \Big(X_j + \sum_{i \neq j} X_i \Big) = F_j \cdot X_j \cdot \left(1 + \sum_{i \neq j} \frac{X_i}{X_j} \right), \tag{3}$$

where F_j is the fraction of the instrument reading that is due to nuclide j. It follows from Equation 3 that:

$$F_j = \frac{1}{1 + \sum_{i \neq j} X_i / X_j}. \tag{4}$$

The activity of nuclide j in the body, Q_j, is related to the instrument reading due to nuclide j, X_j, through the instrument calibration factor:

$$k_j = \frac{Q_j}{X_j}. \tag{5}$$

Consequently, Equation 4 can be written as:

$$F_j = \frac{1}{1 + \sum_{i \neq j} \frac{Q_i}{Q_j} \cdot \frac{k_j}{k_i}}. \tag{6}$$

It is important to note that the factor F_j is expressed as a function of ratios of activities and calibration factors, and that it is not necessary to know their absolute values.

It follows from Equations 3 and 5 that the measured activity of nuclide j, Q_j, can be evaluated as:

$$Q_j = k_j \cdot F_j \cdot X_{\text{net}}. \tag{7}$$

The fraction F_j depends on the distribution of the radionuclide in the body and, therefore, on the time, t, when the measurement was performed as well as on the age, a, of the person measured. The calibration factor k_j depends only on the age of the person. Therefore, Equation 7 should be rewritten as:

$$Q_j(a, t) = k_j(a) \cdot F_j(a, t) \cdot X_{\text{net}}. \tag{8}$$

Assuming that the only radionuclides considered are ^{131}I in thyroid and radiocaesiums (^{134,136,137}Cs) in the whole body, the following equation can be used to calculate the activity of ^{131}I in the thyroid:

$$Q_{\mathrm{I}}(a,t) = k_{\mathrm{I}}(a) \cdot k_{\mathrm{corr}}(a,t) \cdot X_{\mathrm{net}}, \tag{9}$$

where

$$k_{\mathrm{corr}}(a,t) \equiv F_{\mathrm{I}}(a,t) = \frac{1}{1 + \sum_{\mathrm{Cs}} \frac{Q_{\mathrm{Cs}}(a,t)}{Q_{\mathrm{I}}(a,t)} \cdot \frac{k_{\mathrm{I}}(a)}{k_{\mathrm{Cs}}(a)}},$$

where the indices I and Cs stand for ^{131}I and each of the radiocaesiums, respectively.

It follows from the above equations that to determine $k_{\mathrm{corr}}(a, t)$, there are two problems to solve:

(1) the estimation of age-dependent calibration factors, $k_i(a)$, for SPR-68-01 for radiocaesiums (^{134,136,137}Cs) in the whole body and for ^{131}I in the thyroid; and
(2) the estimation of the time- and age-dependent ratios of the activity of the radiocaesiums in the whole body to the ^{131}I activity in the thyroid.

Monte Carlo simulation of the SRP-68-01 response to radiation sources in the human body

The method used to obtain the ratios of the age-dependent calibration factors of SRP-68-01 was a Monte Carlo simulation of radiation transport in mathematical phantoms, representing different ages, and in the detector. The mathematical whole-body phantoms used in this study are based on the family of ORNL phantoms[12,13], which are representative of subjects with the ICRP reference ages[14]—0, 1, 5, 10, 15 years old and adult. For the purpose of the simulation of the thyroid measurements, the ORNL phantoms were modified to be anatomically more realistic in the region of the neck[15]. Figure 1 illustrates the body shape of modified phantoms representing a 5-year-old child and an adult, as examples. A mathematical model of the thyroid gland[15,16] was used in the Monte Carlo simulation. A three-dimensional view of the thyroid models of newborn and adult phantoms is shown in Figure 2. It is seen that the thyroid is represented as a bilobed organ with an isthmus. Each lobe is simulated as a right ellipsoid cut by the trachea cylinder. The neck is approximated by a right circular cylinder.

Another important object of the simulation is the scintillation probe of the survey-meter SRP-68-01. The probe consists of an NaI scintillation crystal (diameter 30 mm, height 25 mm) in an aluminium jacket coupled to a glass photomultiplier tube. Both are surrounded by aluminium tubes and rubber rings. According to the technical documentation of

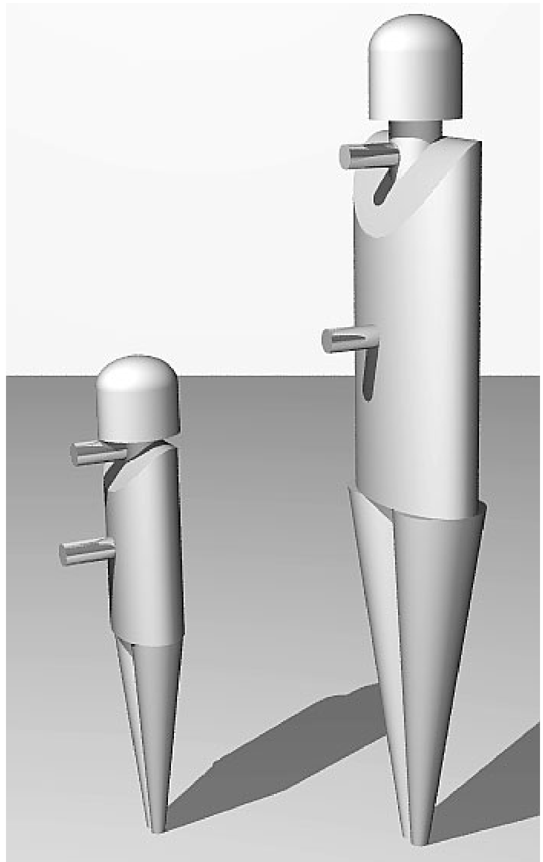

Figure 1. View of mathematical phantoms representing a 5-year-old child and an adult. The detectors are shown as cylinders in contact with the body.

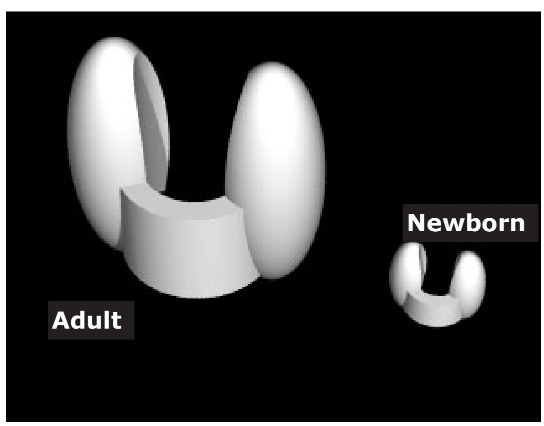

Figure 2. View of mathematical thyroid phantoms of a newborn child and an adult.

the survey-meter, the energy range of registered photons is from 0.02–0.03 to 3.0 MeV. For the purpose of simulation of the detector response to radiation sources, a mathematical model of the detector was developed. The validity of the detector model was verified by comparing the calculated responses with those obtained experimentally using various radiation sources(16).

The entire family of modified ORNL phantoms representing children aged 0, 1, 5, 10 and 15 years old and adults was used to calculate the detector response to gamma-emitting nuclides localised in the thyroid as well as uniformly distributed in the body. For thyroid measurements, the position of the detector was taken to be in contact with the front of the neck and centred against the thyroid. For the measurement of the body content of radiocaesium using the SRP-68-01 instrument, the position of the detector was taken to be near mid-trunk. The detectors are shown in Figure 1 as cylinders against the neck and the chest of the phantoms.

The Monte Carlo calculations were performed using the transport code MCNP4A(17) along with the programs SABRINA(18) and POV-Ray Tracer(19), which were helpful tools to design and visualise the mathematical representation of the whole body phantoms and of the skeleton.

Estimation of age-dependent and time-dependent ^{131}I thyroidal contents and radiocaesium body burdens

The age-dependent and time-dependent ^{131}I thyroidal contents and radiocaesium body burdens were estimated by means of radioecological and metabolic models, in which the transfer of radionuclides from their deposition to the ground to their activities in the body was simulated. The activity of radionuclide i in the thyroid (for ^{131}I) or in the body (for the radiocaesiums) of a person of age, a, at time, t, can be expressed by the following equation:

$$Q_i(a,t) = \int_0^t M_i(a,\tau)\cdot s_i(a)\cdot R_i(a,t-\tau)\cdot \mathrm{d}\tau, \quad (10)$$

where

$Q_i(a, t)$ = activity of the radionuclide i in the thyroid or in the body at time t, Bq;

$M_i(a, \tau)$ = rate of activity intake by the person, Bq d^{-1};

s_i (a) = uptake of radionuclide by the thyroid (for ^{131}I) or to blood (for the radiocaesiums); and

$R_i(a, t)$ = retention function of the radionuclide in the thyroid or in the body.

To estimate the intake of radionuclides, a radioecological model adapted to the local conditions of Belarus was used. Only the consumption of locally produced milk was considered, as it was the most important pathway for iodine and caesium intake by man. At the time of the radionuclide deposition on the ground, leafy vegetables were not ready for consumption even in the southern territories of Belarus. Intake of radionuclides due to inhalation was only important for special groups of population(20). The intake function corresponding to the consumption of contaminated milk was estimated using the following assumptions:

- the radioactive contamination of the ground was caused by a single deposition;
- people consumed locally produced milk and did not change their dietary habits during the first few weeks after the accident;
- people were not relocated to uncontaminated areas; and
- no countermeasure was applied.

Taking into account only milk consumption, the time-dependent intake of a radionuclide i can be estimated as:

$$M_i(a,t) = C_i(t)\cdot V(a), \quad (11)$$

where

$C_i(t)$ = the time-dependent activity concentration of the radionuclide in milk, Bq l^{-1}, and

$V(a)$ = the age-dependent milk consumption rate, l d^{-1}.

The contamination of cow's milk results from the activity intake by the animals and the biokinetics of radionuclides in their bodies. During the first few weeks after the accident, the consumption of pasture grass by cows was the main source of their intake of radioactive materials. The time-dependent radionuclide activity in milk was calculated as(21):

$$C_m(t) = \int_0^t G_i(\tau)\cdot I_\mathrm{g}\cdot \mathrm{TF}_i\cdot \sum_{l=1}^{Li} d_i(l) \cdot \mathrm{e}^{-\left(\lambda_{m,i}(l)+\lambda_{r,i}\right)\cdot(t-\tau)}\cdot \mathrm{d}\tau, \quad (12)$$

where

$G_i(t)$ = activity concentration in grass of radionuclide i, Bq kg^{-1};

TF$_i$ = cow's intake-to-milk transfer factor, d l^{-1};

L_i = number of components of the function describing retention of element i from cow's body;

$d_i(l)$ = fraction of component l = 1, …, L_l;

I$_\mathrm{g}$ = daily intake of grass by cows, kg d^{-1};

$\lambda_{m,i}(l)$ = biological transfer rate for component l, d^{-1};

$\lambda_{r,i}$ = radioactive decay rate of radionuclide i, d^{-1}; and

t = time, counted from the time of deposition, d.

The two components of the biological transfer of caesium (i.e. $L_{Cs} = 2$) in cow's milk were assumed to have the following characteristics[21]: $d_{Cs}(1) = 0.8$, $\lambda_{m,Cs}(1) = 0.46$ d^{-1} and $d_{Cs}(2) = 0.2$, $\lambda_{m,Cs}(2) = 0.046$ d^{-1}. The biological transfer of ^{131}I to cow's milk was described by one component ($L_I = 1$) with $\lambda_{m,I}(1) = 0.99$ d^{-1}.

The activity concentration in contaminated grass is given by:

$$G_i(t) = \frac{1}{Y} \cdot \sigma_i \cdot f_i \cdot e^{-\left(\lambda_{wd,i}+\lambda_{r,i}\right)\cdot t}, \tag{13}$$

where

σ_i = ground deposition (grass + soil) of radionuclide i, Bq m^{-2};

f_i = initial interception factor of radionuclide i by grass, rel. units;

Y = yield of pasture grass at time of deposition, kg m^{-2}; and

$\lambda_{wd,i}$ = elimination rate of radionuclide i from grass due to weathering and growth dilution, d^{-1}.

Retention of the radionuclide from the human body according to the metabolic model of ICRP[14] can be expressed as a linear combination of exponential components of activity decrease:

$$R_i(a,t) = \sum_{n=1}^{N_i} b_i(a,n) \cdot e^{-\left(\lambda_i(a,n)+\lambda_{r,i}\right)\cdot t}, \tag{14}$$

where

$b_i(a,n)$ = fractions of component n; and

$\lambda_i(a,n)$ = elimination rate of component n, d^{-1}, for the stable element (iodine or caesium).

The ^{131}I retention function $R_I(a,t)$ was taken to be monoexponential ($N_I = 1$) while the radiocaesium retention functions $R_{Cs}(a,t)$ were modelled by a sum of two exponentials ($N_{Cs} = 2$). Biokinetic data for stable iodine[20] and caesium[14] are given in Table 1 where the fractions of biological components $b_i(a,n)$ and the corresponding half-life time values $T_i(a,n) = \ln(2)/\lambda_i$ are presented for the different age groups.

From Equation 10 to 14, the age-dependent and time-dependent ratios of the body burden of each of the caesium radioisotopes to the ^{131}I thyroidal content can be written in the following form:

$$\frac{\sum_p Q_{p_{Cs}}(a,t)}{Q_{131_I}(a,t)} = \frac{f_{Cs}}{f_I} \cdot \frac{TF_{Cs}}{TF_I} \cdot \frac{s_{Cs}}{s_I} \cdot \frac{\sum_p \sigma_{p_{Cs}} \cdot E_{p_{Cs}}(a,t)}{\sigma_{131_I} \cdot E_{131_I}(a,t)}, \tag{15}$$

Table 1. Metabolic parameters of stable caesium and iodine used in the calculations for the different age groups.

Parameter	Age, a (y)					
	0.25	1	5	10	15	20
Caesium (uptake by whole body $s_{Cs} = 1.0$)						
$b_{Cs}(a,1)$	—	—	0.45	0.30	0.13	0.10
$b_{Cs}(a,2)$	1.0	1.0	0.55	0.70	0.87	0.90
$T_{Cs}(a,1)$, d	—	—	9.1	5.8	2.2	2.0
$T_{Cs}(a,2)$, d	16	13	30	50	93	110
Iodine (uptake by thyroid $s_I = 0.3$)						
$T_I(a,1)$, d	16	20	30	50	70	100

where index $p = \{134,136,137\}$ denotes the different radioisotopes of caesium and

$$E_{p_{Cs}}(a,t) = \sum_{l=1}^{2} \left\{ \begin{array}{l} b_{Cs}(l) \cdot \lambda_{m,Cs}(l) \\ \cdot \int_0^t e^{-\left(\lambda_{m,Cs}(l)+\lambda_{r,p_{Cs}}\right)\cdot\tau} \\ \cdot R_{p_{Cs}}(a, t-\tau) \\ \cdot \int_0^\tau e^{-\left(\lambda_{wd,Cs}-\lambda_{m,Cs}(l)\right)\cdot\tau'} \cdot d\tau' \cdot d\tau \end{array} \right\} \tag{16}$$

$$E_{131_I}(a,t) = \lambda_{m,I} \cdot \int_0^t e^{-\left(\lambda_{m,I}+\lambda_{r,131_I}\right)\cdot\tau} \cdot R_{131_I}(a, t-\tau) \cdot \int_0^\tau e^{-\left(\lambda_{wd,I}-\lambda_{m,I}\right)\cdot\tau'} \cdot d\tau' \cdot d\tau \tag{17}$$

To determine the time-dependent activity ratio using Equation 15, the following important parameters were analysed:

- the ratios of ^{131}I to radiocaesium activities in ground deposition;
- differences in initial interception factors for ^{131}I and radiocaesium;
- elimination rates of ^{131}I and radiocaesium from grass due to weathering and growth dilution; and
- differences in grass-to-milk transfer factors for ^{131}I and radiocaesium.

The estimation of the time-dependent activity ratios was performed for two regions of Belarus contaminated as a result of the Chernobyl accident. The first scenario applies to the so-called Mogilev spot (Figure 3), which was formed mainly by wet deposition occurring on 28–29 April 1986[22–24]. The Central caesium spot (close to 30 km zone) was chosen as the second region of interest (Figure 3); according to the same references[22–24], it was contaminated mainly by dry deposition on 26–27 April 1986. The contamination pattern of these spots by ^{137}Cs due to the Chernobyl accident is also shown in Figure 3.

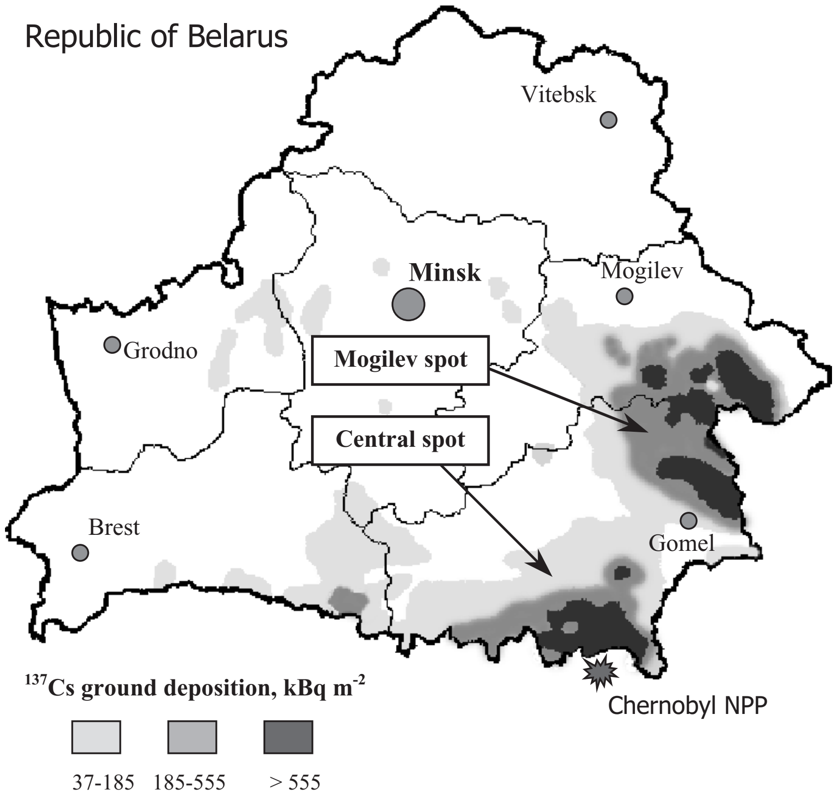

Figure 3. Map of the Republic of Belarus (State Committee on Hydrometeorology of Belarus, 1995). Shaded areas indicate territories contaminated as a result of the Chernobyl accident.

In the following section, ^{137}Cs has been selected to represent the environmental behaviour of radiocaesium as it is the isotope of caesium that has been studied most extensively. Initial interception factors of ^{137}Cs and ^{131}I by vegetation vary depending on the type of deposition. For dry deposition the activity contamination of vegetation depends on the deposition velocity, which depends on the chemical forms of the radionuclide. About 30% of the iodine activity released into the atmosphere during the accident was in gaseous (elemental and organic) form, while the other 70% was attached to aerosols[25]. During atmospheric transport, the ratio of the iodine aerosol and gaseous fractions changed with time; this ratio was measured to be in the range from 0.2 to 0.5 in different locations in Europe[26,27]. The deposition velocity onto vegetation for aerosol bound radionuclides is within an order of magnitude less than for elemental iodine and within an order of magnitude higher than for organic iodine[21]. Taking into account that caesium was only in aerosol form, the ratio of interception factors of caesium and ^{131}I appears to be less than one in the case of dry deposition.

In the case of wet deposition, the interception of radionuclides by grass depends on the ability of radionuclides to be fixed on leaves of vegetation[28]. According to literature data[21], the interception factor by vegetation is higher for caesium than for iodine, when deposition occurs via wet processes.

The values of the ratios of the initial interception factors f_{Cs}/f_I were assessed from the available results of measurements of ^{131}I and ^{137}Cs activities in soil and grass samples[29]. Figure 4 shows the dependence of the ratio of f_{Cs}/f_I on ^{137}Cs ground deposition for settlements in Central and Mogilev spots (correlation coefficient is 0.61, $P < 0.01$). The ratio f_{Cs}/f_I is less than one for areas with lower ^{137}Cs deposition density, which had been contaminated mainly by dry deposition. For the territories with higher contamination, which resulted from wet deposition, the ratio f_{Cs}/f_I is greater than one. The observed dependence is in agreement with literature data.

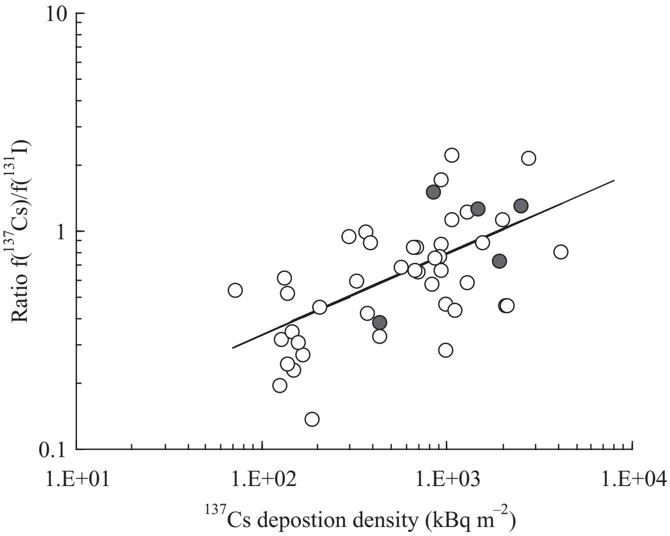

Figure 4. Ratio of coefficients $f(^{137}Cs)/f(^{131}I)$ as a function of ^{137}Cs deposition density: open circles, Central spot and filled circles, Mogilev spot.

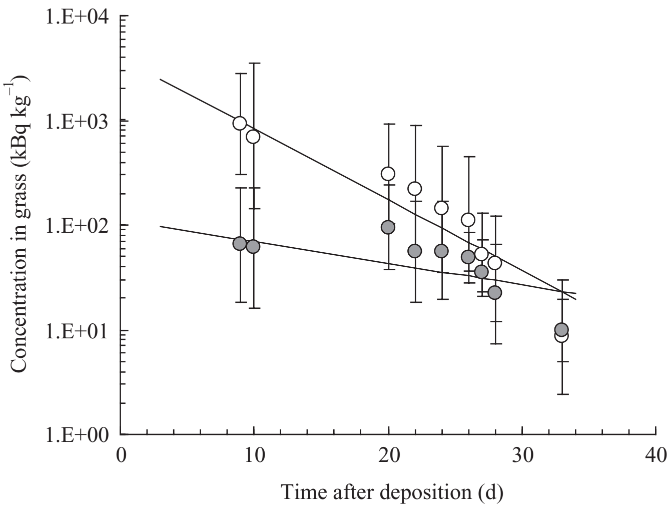

Figure 5. The results of activity concentration measurements in grass: geometric means and geometric standard deviations: open circles, ^{131}I and filled circles, ^{137}Cs.

Because of the difference in deposition types for the Mogilev and Central spots, the following values were used in the calculations: of the ratios of initial interception of ^{137}Cs to ^{131}I by vegetation: $f_{Cs}/f_I = 0.5$ for the Central spot, and $f_{Cs}/f_I = 1.0$ for the Mogilev spot.

Elimination rates of radionuclides from grass were estimated on the basis of available results of gamma-spectrometric measurements of ^{131}I and ^{137}Cs concentration in vegetation in May 1986[29]. Values of $\lambda_{wd,I} = 0.067 \pm 0.016$ d^{-1} and $\lambda_{wd,Cs} = 0.047 \pm 0.014$ d^{-1} were selected for the sum of the weathering rate and of the growth dilution rate for ^{131}I and ^{137}Cs, respectively[29,30]. These values are in good agreement with literature data[31]. Measured activities of ^{131}I and ^{137}Cs in grass (geometric mean) and fitted curves are compared in Figure 5. The error bars shown in Figure 5 correspond to one geometric standard deviation on each side of the geometric mean.

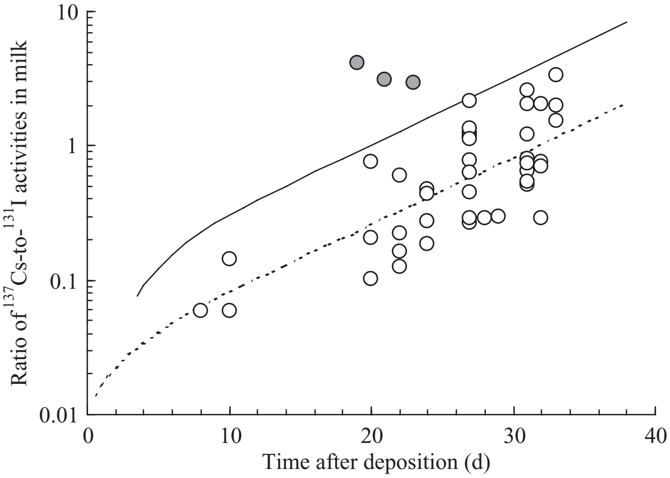

Figure 6. Activity ratio of ^{137}Cs and ^{131}I in milk: calculation (curves) and measurements (dots): solid line, open circles, Central spot; and dashed line, filled circles, Mogilev spot.

Values of transfer factors from grass to milk for ^{131}I and ^{137}Cs were estimated on the basis of the available measurements in feed and milk of cows in Belarus in May 1986. For the ^{131}I transfer factor TF_I, a mean of 3.1×10^{-3} d l^{-1} and a median of 2.3×10^{-3} d l^{-1} were obtained(30). For caesium, the corresponding values of TF_{Cs} were obtained(29): a mean of 3.5×10^{-3} d l^{-1} and a median of 2.8×10^{-3} d l^{-1}. These values are in good agreement with the ^{131}I and ^{137}Cs equilibrium transfer factors for cow's milk reported elsewhere(32). In the present work the same value of the transfer factor 'grass-milk' was selected for ^{131}I and ^{137}Cs: $TF_I = TF_{Cs} = 3 \times 10^{-3}$ d l^{-1}.

The time-dependent activity ratios of ^{137}Cs and ^{131}I in milk calculated using Equations 8 and 9 and measured for the territories of Central and Mogilev caesium spots are shown in Figure 6. For the territory of the Central caesium spot, it was assumed that the pasture season started before the date of main deposition. The pasture season in the Mogilev spot started four days after the date of main deposition(33). As it can be seen from Figure 6, a rather good agreement between the calculated and measured values of the activity ratios of ^{137}Cs and ^{131}I in milk are observed.

Values of parameters used in the calculations of the time-dependent ratios of ^{137}Cs body-burden to ^{131}I thyroidal contents for the populations living in the territories of the Central and Mogilev caesium spots are summarised in Table 2. It was assumed that the ^{134}Cs/^{137}Cs and ^{136}Cs/^{137}Cs activity ratios at the time of the accident were equal to 0.52 and 0.26, respectively.

Table 2. Values of parameters used to calculate the time-dependent ^{137}Cs/^{131}I activity ratios.

Parameter	Notation	Caesium spot	
		Central	Mogilev
^{137}Cs-to-^{131}I ratio in fallout	$\sigma_{137_{Cs}}/\sigma_{131_I}$	1/16	1/8
Ratio of interception factors	f_{Cs}/f_I	0.5	1.0
Ratio of 'grass-to-milk' transfer factors	TF_{Cs}/TF_I	1.0	1.0
Elimination rate of ^{137}Cs from grass, d^{-1}	$\lambda_{wd,Cs}$	0.047	0.047
Elimination rate of ^{131}I from grass, d^{-1}	$\lambda_{wd,I}$	0.067	0.067

RESULTS AND DISCUSSION

Calculation of calibration factors

Age-dependent calibration factors for sources of gamma radiation in thyroid and whole body have been calculated using the following procedure. First, the energy-dependent responses of the SRP-68-01 detector to monoenergetic sources of gamma radiation homogeneously distributed in the whole body and in the thyroid were calculated using MCNP4A. The detector response values calculated for a discrete array of energies are shown in Figure 7. Values for other energies were obtained by interpolation using cubic splines in log–log scale. To calculate the detection efficiency, in terms of counts per unit activity, for a particular radionuclide, the interpolated values need to be convoluted over the photon emission

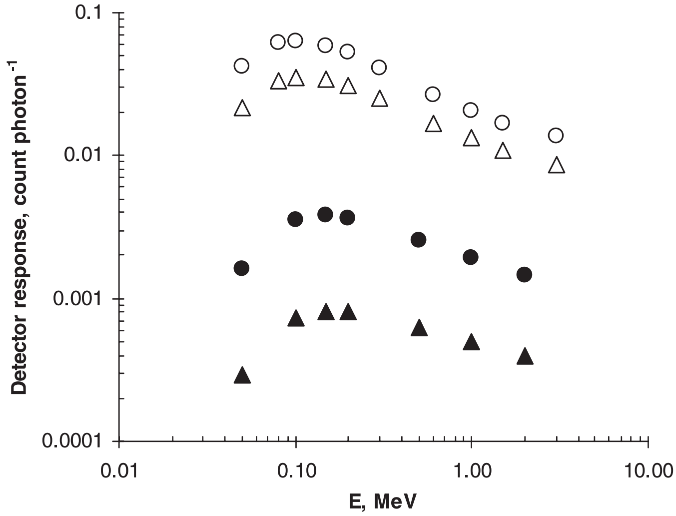

Figure 7. Calculated SRP-68-01 detector responses to monoenergetic isotropic photon sources uniformly distributed in the whole body (white symbols) and in the thyroid (black symbols). The detector is assumed to be placed against the thyroid. Data for 1-year-old child (open circles, closed circles) and an adult (open triangles, closed triangles) are shown as examples.

Table 3. Calculated age-dependent calibration factors for the SRP-68-01 detector for ^{131}I and for radiocaesium (^{134}Cs, ^{136}Cs and ^{137}Cs).

Age (y)	Calibration factor, kBq h μR^{-1}			
	^{131}I	^{137}Cs	^{134}Cs	^{136}Cs
0	0.098	1.33	0.52	0.34
1	0.101	1.70	0.67	0.44
5	0.108	2.52	1.00	0.67
10	0.128	3.74	1.48	1.00
15	0.140	5.55	2.18	1.52
20	0.163	6.85	2.66	1.89

spectrum of the radionuclide. Such a procedure was used to calculate the calibration factors for ^{131}I and ^{134,136,137}Cs that are given in Table 3. The calibration factors for ^{131}I are in reasonable agreement with the available experimental information.

The calculated SRP-68-01 age-dependent calibration factors for ^{137}Cs in the whole body were also compared with available experimental data. The experimental data used were from two sets of experiments. The first experimental dataset(34) was obtained using four age-dependent phantoms with liquid solutions of ^{137}Cs in polyethylene bottles. The second set of data(35) was obtained in 1986 with the assistance of six volunteers who ingested known amounts of ^{134,137}Cs mixture. The calibration factors for the second set of data. recalculated for ^{137}Cs, are presented in Figure 8. In all cases the detector was positioned at mid-trunk. As seen in Figure 8, there is a good agreement between the results obtained from calculations and from measurements.

Age-dependent and time-dependent ^{131}I thyroidal contents and radiocaesium body burdens

Time-dependent activity ratios of ^{134,136,137}Cs isotopes and ^{131}I for six age groups of population living on the territories of Central and Mogilev caesium spots have been calculated using the approach described above. As an example, the ratios of ^{134,136,137}Cs activity in the body to ^{131}I activity in thyroid for newborn, 1-year-old child and an adult are shown in Figures 9 and 10 for two fallout scenarios, respectively. Using Equation 9 and the calculated calibration factors and radionuclide activities in the body, one can estimate the dependence of the correction factor on the time of the direct thyroid measurement and on the age of the subject. Figures 11 and 12 present the variation as a function of time of the thyroid measurement of the correction factor for various age groups for the Central and Mogilev spots, respectively.

It should be pointed out that the procedure described in the present paper is valid only for situations when the background was measured in the absence of the subject. In practice, after the Chernobyl accident, the background was measured by various procedures. Measuring the background without the subject was used in many cases but not always. Alternative procedures consisted in measuring the background near the subject's shoulder (upper arm)

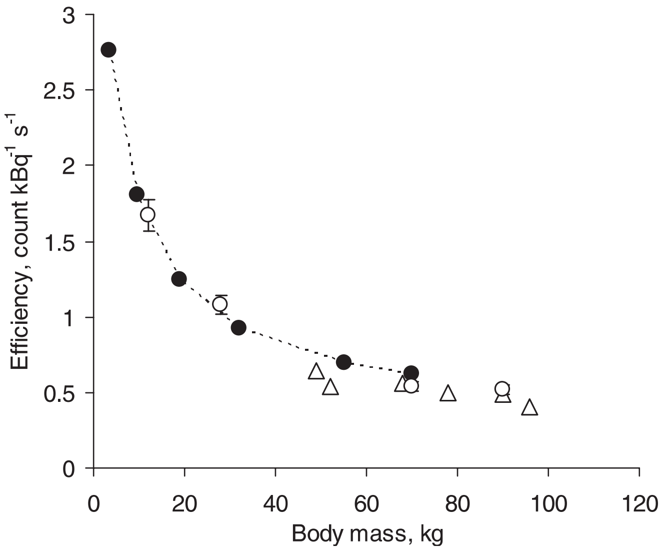

Figure 8. Comparison of measured (open circles—Ref. (34), open triangles—Ref. (35)) and calculated (closed circles – this paper) calibration factors of the SRP-68-01 detector for ^{137}Cs sources homogeneously distributed in the whole body.

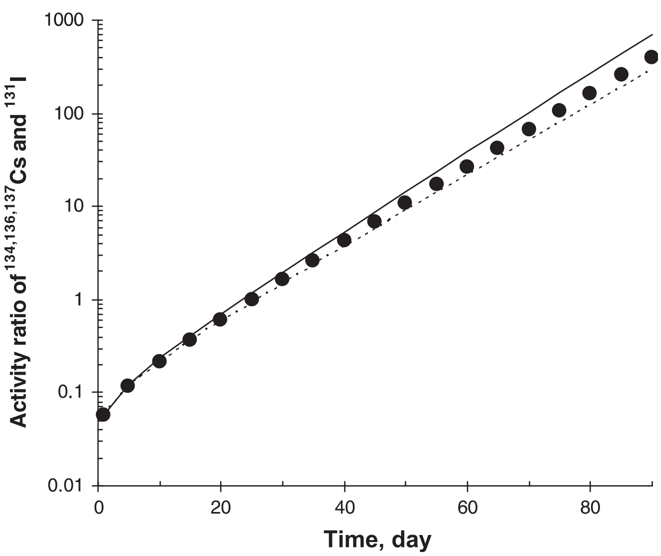

Figure 9. Calculated activity ratio of ^{134,136,137}Cs in the whole body and of ^{131}I in the thyroid for the Central spot. Shown are data for adult (closed circles), newborn (solid line) and 1-year-old child (dashed line).

and near the liver. These alternative methods of background measurement automatically included the contribution of the caesium isotopes in the human body as well as other radiation sources like external contamination, and led to compensation of the errors that are described by the correction factor presented above. Therefore, it should be clearly understood that results presented here characterise the maximum errors among several possible procedures of background measurement.

For a given intake of ^{131}I, the thyroid dose, D^*_{thyr}, is proportional to the activity of ^{131}I in the thyroid at the time of measurement, which in turn is derived from the result of the measurement, X_{meas}:

$$D^*_{\mathrm{thyr}} \sim Q_{\mathrm{I}}(t) \sim k_{\mathrm{corr}}(t) \cdot X_{\mathrm{meas}}. \qquad (18)$$

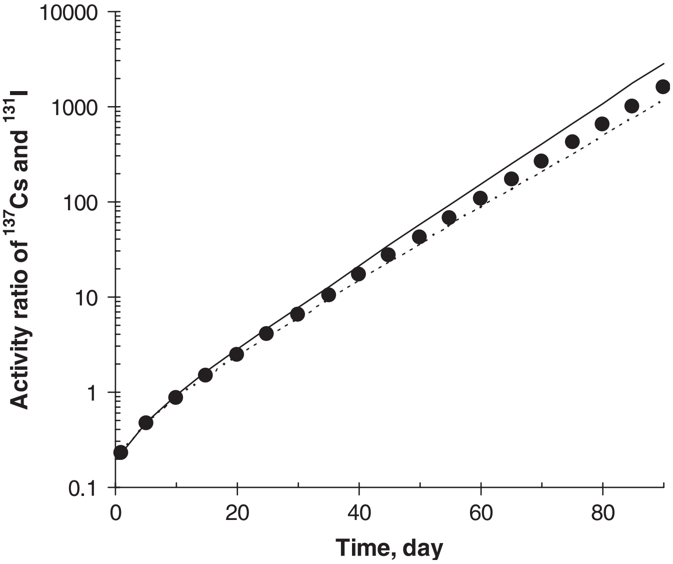

Figure 10. Calculated activity ratio of ^{134,136,137}Cs in the whole body and of ^{131}I in the thyroid for the Mogilev spot. Shown are data for adult (closed circles), newborn (solid line) and 1-year-old child (dashed line).

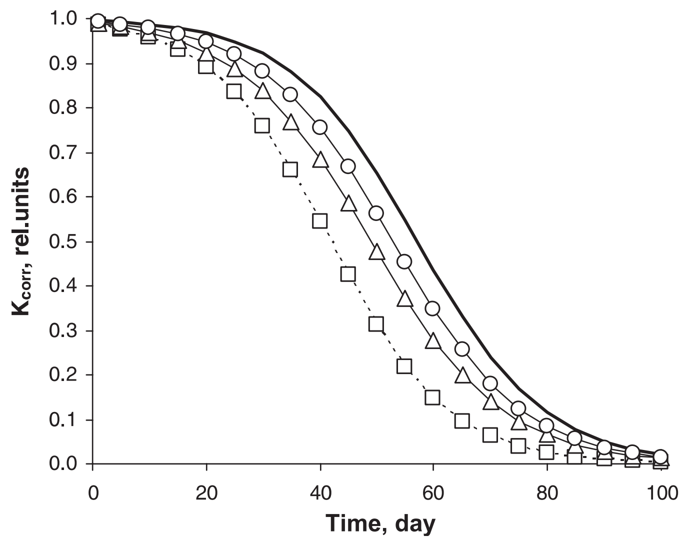

Figure 11. Variation of the correction factor as a function of time following fallout in the Central spot. Shown are values for adult (solid line), newborn (open squares), 1-year-old (open triangles) and 5-year-old (open circles) children.

Therefore, the correction factor is related to the error made in the dose estimate when the result of the measurement, X_{meas}, is entirely attributed to ^{131}I and does not take into account the fact that some of the signal is caused by the caesium isotopes distributed in the whole body. The additional irradiation of the detector by caesium isotopes distributed in the body leads to an overestimation of the thyroid dose by ^{131}I; the value of the overestimation or relative error in the thyroid dose estimate that occurs when the radiocaesium contribution to the result of the thyroid measurement is ignored can be expressed as:

$$\Delta = \frac{D_{\mathrm{thyr}} - D^{*}_{\mathrm{thyr}}}{D^{*}_{\mathrm{thyr}}} = \frac{1 - k_{\mathrm{corr}}}{k_{\mathrm{corr}}}, \tag{19}$$

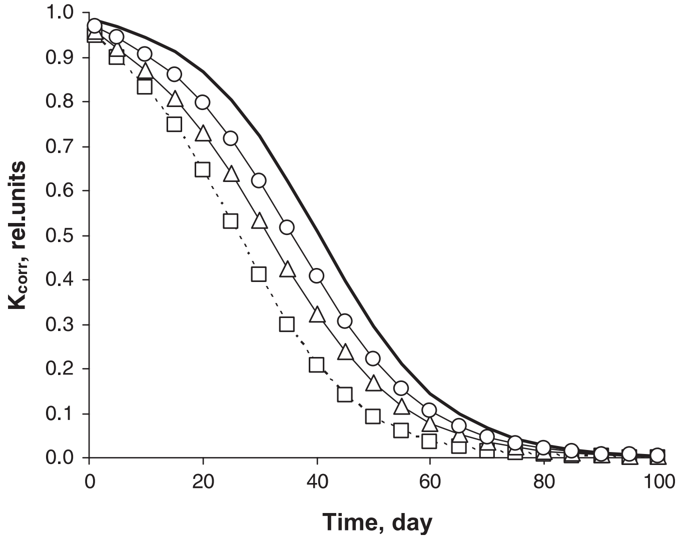

Figure 12. Variation of the correction factor as a function of time following fallout in the Mogilev spot. Shown are values for adult (solid line), newborn (open squares), 1-year-old (open triangles) and 5-year-old (open circles) children.

Table 4. Overestimation (or error) of the thyroid dose that occurs when the radiocaesium contribution to the result of the thyroid measurement is ignored (see Equation 19).

Date of the thyroid measurement	Relative error in the thyroid dose, Δ (%)					
	Newborn	1 y	5 y	10 y	15 y	Adult
Central spot						
May 1	+2.8	+2.2	+1.5	+1.2	+0.09	+0.08
May 11	+8.4	+5.9	+4.1	+3.2	+2.5	+2.4
May 26	+36	+22	+15	+12	+10	+9.7
June 10	+154	+80	+57	+46	+41	+38
June 25	+657	+293	+212	+175	+164	+147
Mogilev spot						
May 3	+11	+8.6	+6.1	+4.8	+3.6	+3.4
May 13	+34	+24	+17	+13	+10	+9.6
May 28	+144	+88	+61	+48	+41	+39
June 12	+615	+321	+226	+183	+165	+152

where D_{thyr} and D^*_{thyr} are the uncorrected and corrected values of the thyroid dose, respectively.

The analysis of the time-dependent and age-dependent correction factors shows that the effect of radiocaesium on the thyroid dose is higher for the Mogilev spot than for the Central spot, and is higher for young children than for teenagers. Table 4 presents the error values calculated using Equation 19. It is seen in Table 4 that, for conditions typical of the Central caesium spot the relative error caused by the presence of radiocaesium in the body of an adult is ~10% for a measurement 30 days after the accident (May 26) and 38% for a measurement 45 days after the accident (June 10). Corresponding values are 15 and 57% for a 5-year-old child and 22 and 80% for a 1-year-old child, respectively. Thus, in the conditions of the Central spot, the error in the thyroid dose caused by radiocaesium in the body remains in an acceptable range when the thyroid measurement was conducted during the first month after the accident. On the other hand, in conditions typical of the Mogilev spot, the relative errors are much greater: ~60 and 90% for 5- and 1-year-old children when the thyroid measurements were conducted one month after the accident, and 230 and 320% for 5- and 1-year-old children when the thyroid measurements were conducted ~45 d after the accident.

CONCLUSIONS

The substantial increase in the incidence of thyroid cancer in children following the Chernobyl accident has attracted great attention to the problems of thyroid dose reconstruction. The reliability of the thyroid dose estimates is a crucial issue in the determination of the dose–response relationship. It is therefore very important to analyse the sources of uncertainties in the reconstructed thyroid dose estimates. In this paper, the influence of the caesium radioisotopes distributed in the body on the signal recorded by an instrument performing the measurement of ^{131}I activity in the thyroid is evaluated. This problem is of high importance for direct thyroid measurements performed in Belarus following the Chernobyl accident because those measurements were performed mostly by dosimetric and radiometric devices without collimators.

The estimation of the radiocaesium contribution to the results of the direct thyroid measurements made by means of a SRP-68-01 radiometer was made using a Monte Carlo method and a radioecological model adapted to the conditions of Belarus. The Monte Carlo method was used to estimate calibration factors for the SRP-68-01 radiometer for a range of gamma energies, for two locations of the detector against the human body, and for various body sizes. To model the transport of gamma radiation within the human body, the modified mathematical phantoms of ORNL-ICRP were used. The radioecological model was used to estimate the time-dependent contents of ^{131}I in the thyroid and of ^{134,136,137}Cs in the whole body due to radioactive fallout in two regions of Belarus following the Chernobyl accident. The results obtained with the Monte Carlo calculations and the radioecological model led to the estimation of the relative contributions of the activities of radioiodine in the thyroid and of radiocaesium in the body to the readings of the SRP-68-01 radiometers during the direct thyroid measurements. It is demonstrated that, for the two regions considered and for typical population behaviours, the activity ratio of radiocaesium in the body and of radioiodine in thyroid could be expressed through ratios of parameter values (see Equation 15). Consequently, coefficients presented above can be applied to correct results of measurements of those population groups, whose place of residence and behaviour correspond to the conditions that were considered.

It is shown that for conditions specific to the territories of the Central caesium spot the relative error caused by the contribution of radiocaesium in the body does not exceed 30% when the direct thyroid measurements are made during the first month after the accident. But in conditions typical of the northern Mogilev spot the influence of the additional irradiation from radiocaesium is considerably higher: by the end of the first month the corresponding error varies from 40% for adults to 90–140% for children aged 0–2. It is seen from the results obtained that the error in the thyroid dose is maximal for very young children who resided in the Mogilev spot. The use of correction coefficients in the analysis of the results of direct thyroid measurements performed in May 1986 will lead to more accurate thyroid dose estimates and may make it possible to use some of the measurements performed in June 1986.

However, it must be kept in mind that the results presented in Table 4 are only valid when background was measured in the absence of the subject. Only this situation leads to the errors in the dose estimates that are presented in Table 4. Provided the background was measured by an alternative method—close to some part of the human body—the errors in thyroid doses caused by radiocaesium contribution to measurement results would be considerably lower.

ACKNOWLEDGEMENT

Authors gratefully acknowledge Prof. A. G. Mrochek, Prof. Ya. E. Kenigsberg, and Dr V. F. Minenko (Minsk, Belarus) for the support of the investigations, and Drs V. T. Khrouch, Yu. I. Gavrilin, and S. M. Shinkarev (State Scientific Center 'Institute of Biophysics', Moscow, Russia) for fruitful discussions and valuable comments. The work presented in this publication was performed with financial support provided by the US National Cancer Institute, the US Department of Energy, and the Ministry of Health of Belarus within the framework of 'The Belarus–American Scientific Protocol on Study of Childhood Thyroid Cancer and Other Thyroid Diseases in Belarus following the Chernobyl Accident'.

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